ON-BOARD PROCESSING FOR ATTITUDE CONTROL OF APPLE

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ABSTRACT

APPLE, India's first three axis stabilised communication satellite, was launched by the ARIANE launcher on June 19,1981. The communication payload operates in C-band (4-6 GHz) and facilitates experiments in communication technology and its applications. Attitude and Orbit control System (AOCS) of APPLE, whose on orbit performance is satisfactory despite the non deployment of one of the solar panels, is briefly described. Various functions on the Attitude Control Electronics (ACE) are described with details on processing schemes for Pulsewidth Pulse Frequency Modulator, Yaw error computation using hybrid SINE convertor, Magnetic torquer control and Thruster selection. Further, future trends in onboard processing for communication satellites are highlighted.

INTRODUCTION

India's first experimental communication satellite, APPLE, was launched by the third developmental flight of the European Space Agency's (ESA) launcher ARIANE, on June 19,1981. It is a three axis stabilised spacecraft with sun tracking solar panels and is positioned at 102°E longitude, providing bidirectional communication in C-band (4- 6 GHz) over India. The main mission objective was to build an experimental three axis body stabilised geostationary communication satellite at Indian Space Research Organisation (ISRO) with its own Apogee Boost Motor and Attitude and Orbit Control System (AOCS). It is being used to conduct experiments in communication technology with applications in domestic communication, radio networking, data relay, remote area communication, etc.

Three axis stabilisation of APPLE was achieved on June 23,1981 even with one solar panel undeployed. After a couple of orbit control manoeuvres, on July 16,1981, the spacecraft was parked at the designated slot in the geosynchronous orbit. The communication transponders were switched ON and the performance of the overall spacecraft and the communication payload is satisfactory. Further, communication

experiments in the field of multiple access voice and data communication, radio and television networking, teleconferencing and computer interconnection, etc., are under progress. APPLE mission is a success fulfilling the objectives of building three axis stabilised satellite, having experience in on-orbit (station keeping) management and conducting experiments in communication technology and its applications, and becoming forerunner for future domestic communication satellites.

The Attitude and Orbit Control System (AOCS) of APPLE does the important function of pointing the antenna towards earth, with an accuracy of 0.25°in pitch and roll and 0.4° in yaw, and correcting the orbit despite the disturbance forces acting on the spacecraft. With a general outline on AOCS, this paper describes in detail its functions, onboard processing requirements and the hardware realisation. Further, future trends in onboard processing, to meet the growing demand for long life and precise attitude control of future communication satellites are highlighted.

ATTITUDE AND ORBIT CONTROL SYSTEM (AOCS)

The Attitude and Orbit Control System, which consists of Attitude Control Electronics (ACE), a variety of attitude sensors such as Earth sensors, 4π steradian sensors, Digital aspect angle sensor, etc; and Momentum Wheel, Magnetic torquers and Reaction Control System (RCS) as actuators, is shown in Fig. 1. It is a conventional closed loop system controlling all the three axes, pitch, roll and yaw, of the spacecraft, within 0.15°, 0.15° and 0.4° respectively. However, during station keeping operation, Yaw error can be as high as 1.5°, while the pitch and roll errors are controlled within 0.25°. Attitude control electronics receives signals (error information) from sensors and generates control signals for actuators in accordance with control algorithms, so as to correct the errors within the given limits and provide the required orientation, despite the disturbing forces acting on the spacecraft. The system can also be controlled by telecommand from ground. Also, it interfaces with telemetry, for transmitting the housekeeping information and power system (Fig.2). The spacecraft is spin stabilised during the transfer orbit phase, from injection in the eliptical orbit by the launcher to Apogee Boost Motor (ABM) firing for circularising the orbit. The spin rate and spin axis orientation are controlled through ground commands, so that the spin rate is increased to 60 rpm from the initial spin of 10 rpm and the spin axis is in the nominal AMF attitude. After ABM firing, the spacecraft is despun for solar panel deployment.

During sun and earth acquisition of the spacecraft all the three axes, pitch, roll and yaw, are controlled by hydrazine thrusters (RCS), Pulsewidth Pulse Frequency Modulator (PWPFM) logic and sun sensors/earth sensors. Non deployment of one of the solar panels has caused difficulties in sun acquisition as two segments of the 4π steradian sensor were covered by the panel. After initial acquisition, during on orbit operational phase, the

PWPFM and momentum wheel control the pitch axis within 0.15°, by utilising the reaction torque obtained by varying the wheel speed in accordance with earth sensor pitch output. The momentum wheel speed variation is limited to ±10% of the nominal bias speed (3500 rpm) by either automatic or manual momentum dumping (desaturation) using thrusters. The roll error is sensed by the earth sensor and is automatically controlled by continuously varying the magnetic torquer current and also by actuating the thrusters, when the error exceeds ± 0.15°. Non deployment of North solar panel introduces large solar radiation disturbance torques, and hence the magnetic torquer alone is unable to correct the roll error totally. So, ground commands are also given to limit the error. The pitch momentum bias gives gyroscopic stiffness about yaw and the yaw error is automatically controlled as it gets converted to roll error after every quarter orbit.

Orbit Control (station keeping) using thrusters, corrects the orbit drifts introduced by the perturbing forces. As the momentum wheel and normal roll/yaw controllers cannot handle the large attitude errors developed during station keeping, all the three axes are controlled by thrusters and PWPFMs logic during station keeping, As separate yaw sensor is not available, yaw error is computed onboard using the Aspect and Solar angles and satellite position. Further, provision exists for biasing the pitch and roll error outputs, to compensate for long term drifts/offsets and seasonal variations, if any.

ATTITUDE CONTROL ELECTRONICS

Attitude Control Electronics (ACE), the heart of the attitude control system does the onboard processing needed for attitude control, and generates actuating signals for momentum wheels, magnetic torquers and thrusters as a function of attitude errors and ground commands, to provide the required orientation. While most of the functions are controlled in an autonomous manner, system operating modes, various control parameters, and certain functional executions are controlled by telecommands from ground. Performance and status of the onboard system is monitored through telemetry. The following gives the various functions performed by the Attitude Control Electronics (Fig.3).

A. Transfer Orbit phase:
   Spin rate and spin axis orientation control.

B. On Orbit phase:

   i) Three axis acquisition using PWPFM and thrusters, with provision to select various sensors for the controllers.

   ii) Pitch axis control using momentum wheel and momentum dumping.

iii) Roll/Yaw control using magnetic torquer and hydrazine thrusters.

iv) Yaw error computation.

v) Station keeping and three axis control during station keeping.

C. Thruster selection as a function of various controller outputs.

D. Biasing for earth sensor pitch and roll outputs and collection of house keeping information.

Some of the major functions and their hardware realisation are described below. The characteristics of APPLE Attitude Control Electronics is given in Table. I.

PULSEWIDTH PULSE FREQUENCY MODULATOR (PWPFM)

The pulsewidth pulse frequency modulator logic (Fig. 4) used for momentum wheel and thruster control, has the advantages of wide dynamic range, inherent provision for incorporation of damping (rate feedback) without need for generation of rate of change of the output - pseudo rate damping-, and dead zone around the operating point and hence better noise immunity. It generates the bipolar signal, Vo, whose polarity, pulsewidth and period depend on the input signal amplitude, polarity and rate of change of input. For positive input voltage, the integrator output V1 increases till the voltage V2 crosses the threshold e_{th} in the hysteresis comparator and the output changes over its state from zero to -v. Due to effective negative feedback of the output signal, the integrator starts discharging and as soon as the voltage V2 reaches zero, the comparator output goes to zero and the process repeats. The rate effect (damping) is introduced by the factor K1 at the summer. The modulator exhibits similar behaviour for -ve input voltage, with the output polarity reversed. Both the pulsewidth and pulse frequency change with the input signal, therby effectively controlling the duty cycle. The static characteristics of the PWPFM are shown in Fig.5.

YAW ERROR COMPUTATION

As the yaw error information is not directly available from attitude sensors, it is computed onboard as follows:

$$\text{Yaw error, } \psi = \frac{-\sin\sigma + K_1 \sin S}{\frac{1}{2}\left[K_2 \sin(K_{sp}+S) + K_3 \sin(K_{sp}-S)\right]}$$

where ψ is in radians and K_1,K_2 and K_3 are constants. The onboard aspect sensor gives the solar aspect angles, σ, as a 6 bit Gray Coded digital word. The satellite position, K_{Sp}, increments by 1.4° for every 5.6 min.(360° per day). The solar angle, S, which changes by about 1° per day, and the satellite position, K_{Sp} , are preset by telecommand.

As the variables, σ, K_{SP} and S are digital data and the yaw error is required as an analog voltage to feed to the analog controller, and also during the development of the circuit space proven and low power microprocessors and PROMs were not popular for direct digital computation, a novel hybrid technique using operational amplifiers, hybrid SINE convertors and analog dividers, is used for yaw error computation (Fig.6).

HYBRID SINE CONVERTOR

The hybrid SINE convertor (Fig.7) accepts the input, θ, as a digital data and generates an analog output proportional to sin θ. The bisic principle is to sample the sine wave at an instant proportional to θ and hold the sampled value till the next sample. The SINE wave signal of frequency f, the input to the sample and hold circuit, is generated by filtering the square wave of frequency f, obtained by dividing the oscillator frequency $f.2^n$ (where n is the number of binary bits in the input data, θ). The input θ is fed to the preset inputs of the n bit presettable down counter. At the starting of the every cycle of the sine wave, the counter is preset to θ, by the zero crossing detector. The counter counts down from θ, at a frequency of $2^n.f$.

When the counter goes to zero at t_1 ($=\theta/2^n.f$) it generates control signal for the sample and hold to sample the input sine wave. The sampled value is held till the next sample and the process, repeats.

Sample and Hold input $E_i(t) = E \sin 2\pi ft$.
Output, $Eo = E_i(t_1) = E \sin (2\pi\theta/2^n)$
$= E \sin\theta$, as 2^n corresponds to 2π.

As low power space proven monolithic analog dividers were not available, time division multiplier/divider using Pulsewidth pulse hight modulation is built in-house using operational amplifiers and FETs.

MAGNETIC TORQUER CONTROL

Closed loop magnetic attitude control is used for the first time for roll/yaw control and damping out mutational motion of three axis stabilised geostationary satellite, saving considerable amount of fuel and hence extending the life of the mission. The magnetic torquer placed along the roll axis of the spacecraft interacts with the geomagnetic field and

generates required control torque. The roll error, ϕ, consists of two components, ϕ_n at nutational frequency of 1/30 HZ and ϕ_r at the orbital frequency of one cycle per day($\phi = \phi_n + \phi_r$). For effective nutation damping and roll error control, the torquer is excited with a signal proportional to $\phi_n - \phi_r$ (Fig.8). The nutation frequency component ϕ_n is filtered out and combined with ϕ to generate the signal $\phi_n - \phi_r$. Filtering the signal at 1/30 HZ is a tricky job and bandpass filter with bulky capacitors are used. The power amplifier, which drives the torquer, has an output of $50(\phi_n - \phi_r)$ if the momentum wheel-1 is selected and $-50(\phi_n - \phi_r)$, if the redundant momentum wheel-2, which has opposite momentum vector direction due to mounting and configuration constraints, is selected.

Thruster Selection

The Reaction Control System (RCS) has sixteen thrusters grouped into two functionally redundant blocks. The Thruster Selection Logic (TSL) selects different combination of thrusters depending upon the various functions performed and thruster block selected and drives the appropriate thrusters through thruster dirvers. The thruster selection logic, realised using logic gates, receives twenty four inputs from various controllers and generates sixteen outputs.

Attitude Control Electronics which is very critical for the mission success, has hot redundancy to mask any single point failure, by switching over to the redundant system through telecommand. Very low power consumption and high reliability are achieved by using MIL qualified CMOS 4000 series digital ICS, operational amplifier 108A, and other discrete active and passive components. As prolonged exposure to space radiation at geostationary orbit degrades the performance of the components/system, radiation hardened (mega rad) components with adequate shielding are used. On orbit performance of the system is satisfactory.

FUTURE TRENDS IN ONBOARD PROCESSING

As the control system requirements become stringent, requiring better pointing accuracies for future communication and direct TV broadcast satellites, the onboard computational accuracy and processing requirements grow enormously necessitating microprocessor based programmable digital attitude control system. In addition to easy implementation fault tolerance and self diagnostics features, simple reprogramming of the control memory provides multimission adaptability to the system, thereby reducing the cost and time required to produce flight worthy hardware.

Automatic functional reconfiguration of the system involves detection and isolation of faulty element/system in real time and substitution of redundant element and/or modification of control algorithms to mask the effect of failures. It gives high reliability

and uninterrupted performance and service, despite the failures which might occur on orbit during the long life of the mission and would have been catastrophic to the mission otherwise.

System dynamics of spacecrafts with large appendages (solar arrays, antenna, etc.) cannot be reliably tested at ground and unusual and unexpected problems are likely to occur during the very long (10-15 years) on orbit life. To provide acceptable level of system performance despite the above shortcomings and to meet the unforseen requirements the Attitude and Orbit Control System (AOCS) is to be “remotely programmable”. Depending upon the failures/requirements new control algorithms can be devised and the onboard system can be reprogrammed from ground through telecommand, to carryout the desired function. Also, parameters/controllers gains can be modified to confirm to the actual conditions that exist on orbit, thereby improving normal performance of the system. Thus, remote programmability of the attitude control system enhances the probability of mission success. They are feasible, within the power and weight constraints, with the availability of space proven microprocessors, memories and other support circuits.

CONCLUSION

With a brief description on APPLE attitude control system, the onboard processing requirements of the control electronics are discussed. Processing schemes for Pulsewidth Pulse Frequency Modulator(PWPFM), yaw error computation using hybrid SINE convertor, Magnetic torquer control and thruster selection are described in detail. Also, the future trends in onboard processing for communication satellites are highlighted, with special reference to availability of space proven microprocessors. The on orbit performance of APPLE is satisfactory.

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T A B L E - 1

CHARACTERISTICS OF APPLE ATTITUDE CONTROL ELECTRONICS

APPLE	:	India's First Experimental Communication Satellite, Launched on JUNE 19, 1981.
TYPE OF STABILISATION	:	3-axis body stabilisation with sun tracking panels.
ACTUATORS	:	Redundant Momentum Wheels Magnetic Torquers Reaction Control System (RCS)
SENSORS	:	Earth Sensors, Sun Sensors.
CONTROL ELECTRONICS:		
TYPE	:	Redundant hardwired analog/ digital controllers.
FUNCTIONS	:	Attitude Control, Station keeping, Onboard yaw error computation.
TELECOMMAND	:	ON/OFF and Pulse type - 49 Data - 6
TELEMETRY	:	Digital channels - 14 Analog channels - 4
POWER CONSUMPTION	:	2.0 W
PACKAGE SIZE	:	215 x 160 x 220 m^3 (Two Nos.)
WEIGHT	:	6.05 Kg (total)
INTERFACES WITH	:	Actuators, Sensors, Power Telecommand and Telemetry.

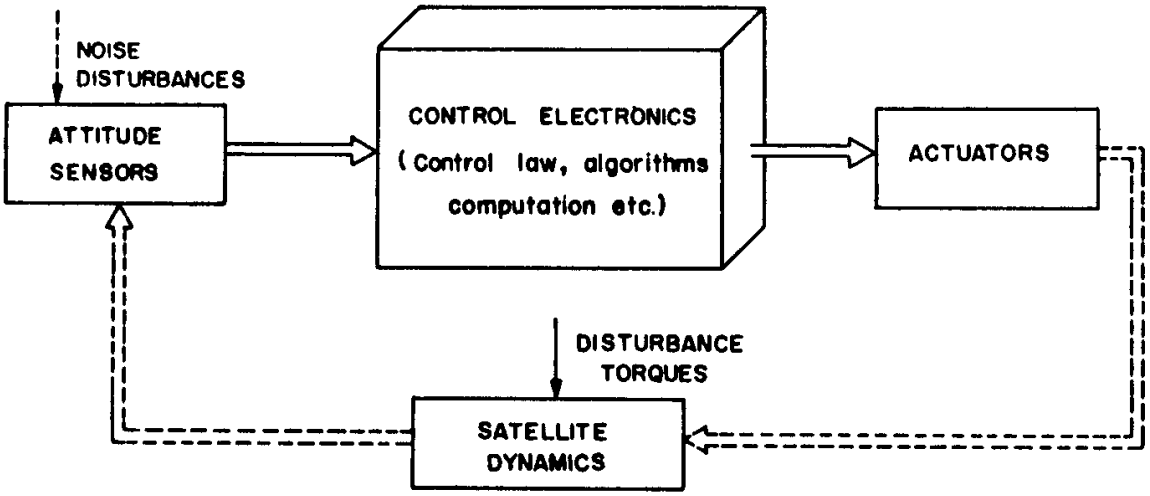


FIG. 1. BLOCK DIAGRAM OF ATTITUDE AND ORBIT CONTROL SYSTEM OF APPLE

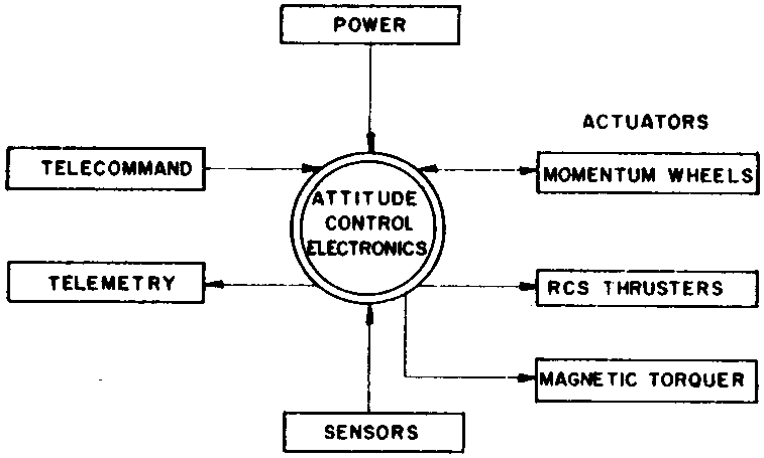


Fig. 2 ATTITUDE CONTROL ELECTRONICS-INTERFACE WITH OTHER SYSTEMS.

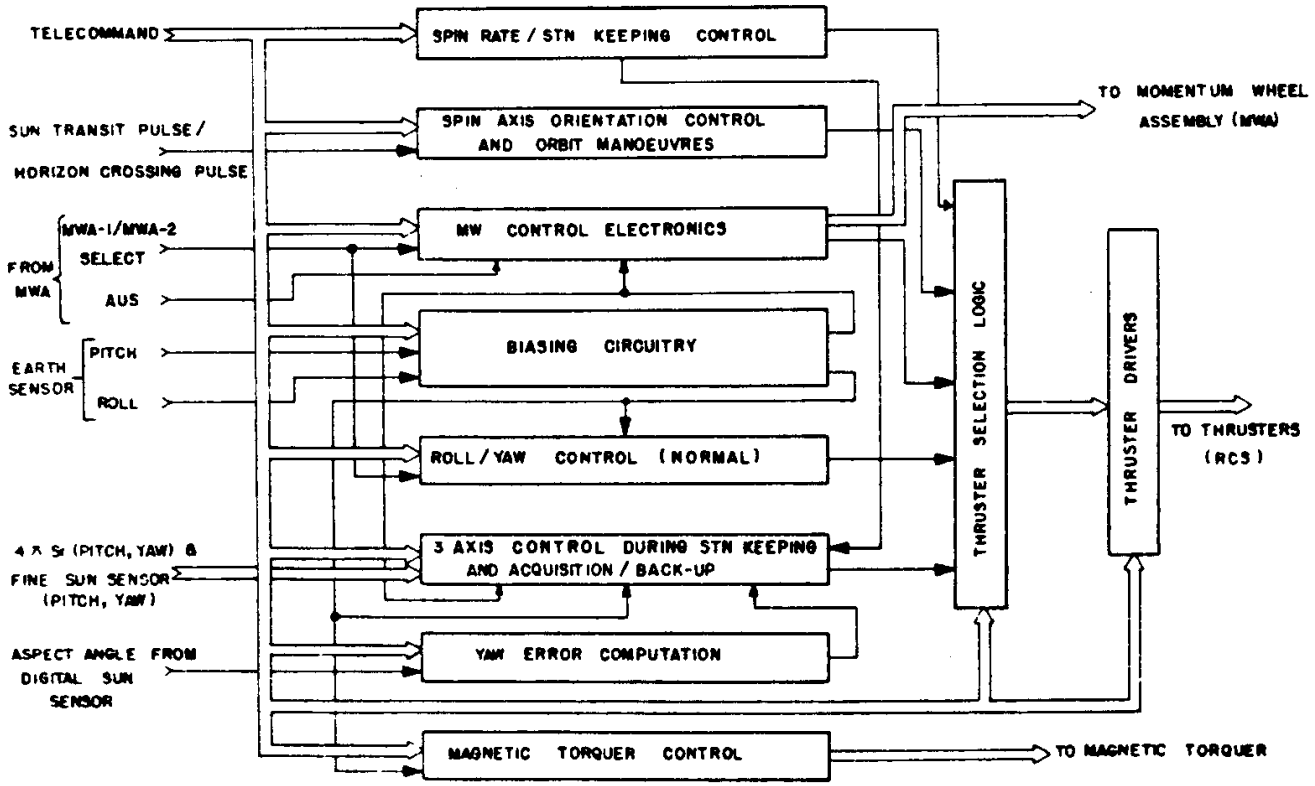


FIG 3. FUNCTIONAL DIAGRAM OF ATTITUDE CONTROL ELECTRONICS

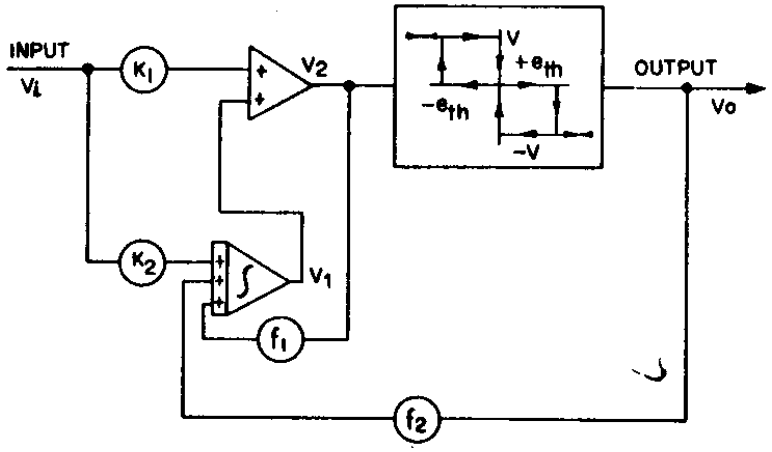


FIG. 4. BLOCK SCHEMATIC OF PULSE WIDTH PULSE FREQUENCY MODULATOR

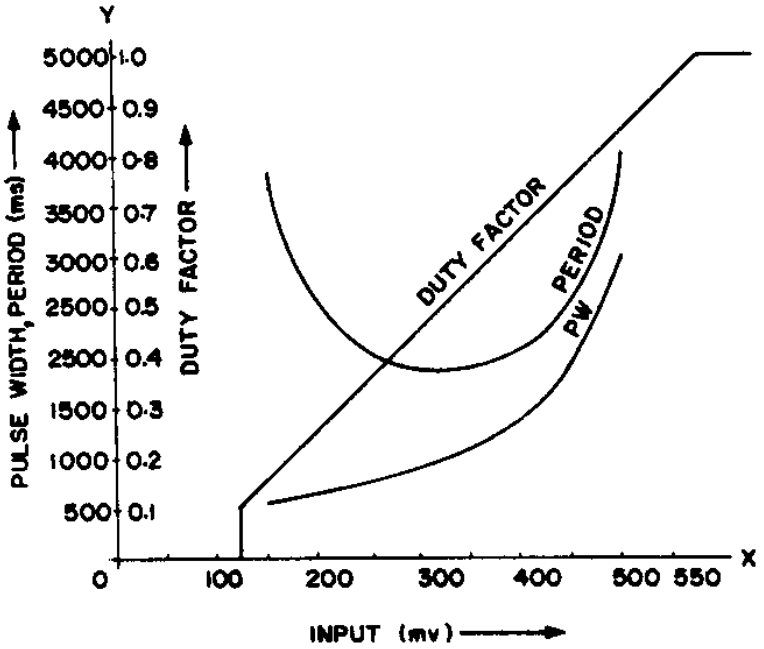


FIG. 5. CHARACTERISTICS OF PWPFM

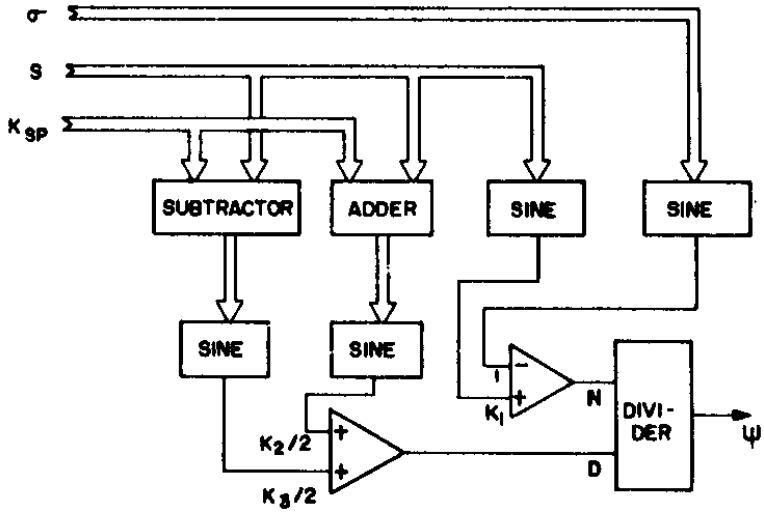


FIG.6. YAW ERROR COMPUTATION

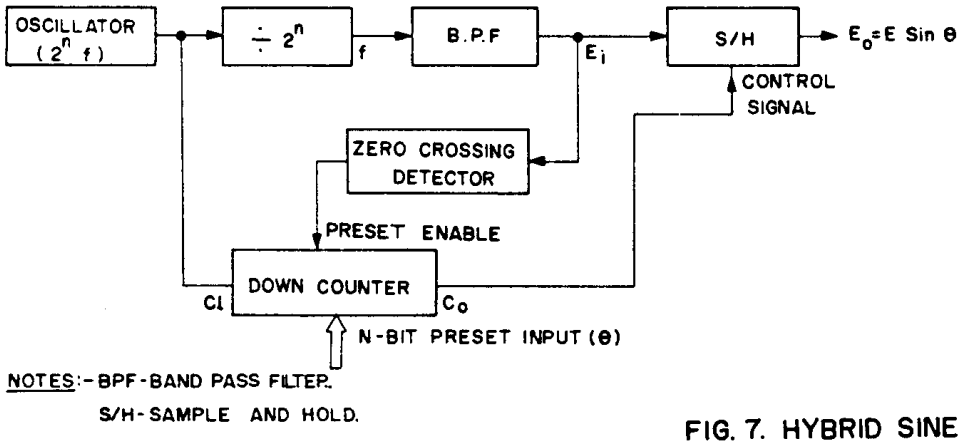


FIG. 7. HYBRID SINE

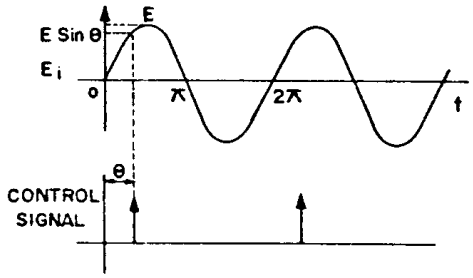
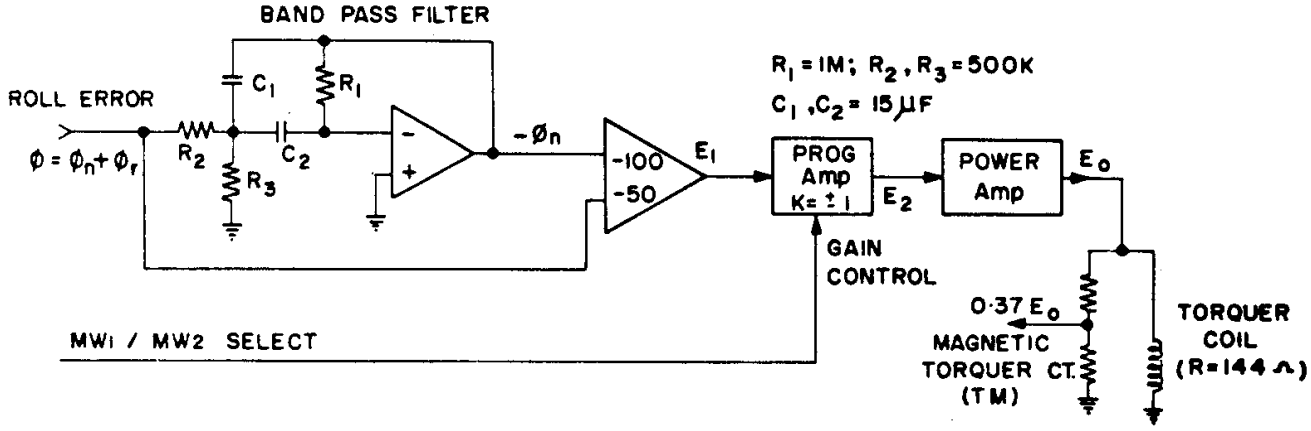


FIG. 7. HYBRID SINE CONVERTOR



$E_2 = 50\,(\phi n - \phi r)$ IF MWA1 IS SELECTED

$= -50\,(\phi n - \phi r)$ IF MWA2 IS SELECTED

FIG. 8. MAGNETIC TORQUER CONTROLLER